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Moisture Buffer Effect and its Impact on Indoor Environment

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Abstract

The moisture buffer effect of building materials may have great influence on indoor hygrothermal environment. In order to characterize the moisture buffering ability of materials, the basic concept of moisture buffer value (MBV) is adopted. Firstly, a theoretical correction factor is introduced in this paper. The moisture uptake/release by hygroscopic materials can be calculated with the factor and the basic MBV. Furthermore, the validation of the correction factor is carried out. The impact of moisture buffering on indoor environment is assessed by using numerical simulations. The results show that the application of hygroscopic materials with large MBV values could reduce the fluctuation of indoor relative humidity, thus decreasing the energy demand for dehumification. The potential energy saving rate of the test building in temperate climates and semi-arid climates could be up to 25-30%. Finally, the relationship between MBV and potential energy saving rate is discussed.

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Keywords: Moisture Buffer Effect; Hygroscopic material; Test method; Indoor humidity condition; Building energy conservation

1. Introduction

Buildings consume almost 40% of global energy [1]. The energy consumption of mechanical heating, ventilation and air-conditioning (HVAC) system in developed countries accounts for half of the energy use in buildings. Many studies have been carried out to investigate the use of passive approaches, systems and materials to minimize the use of HVAC system and consequently reduce the energy use in buildings [2]. One promising approach is using novel materials to control the indoor hygrothermal conditions passively.

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Indoor humidity is an important parameter, which has a significant effect on thermal comfort, building loads, and indoor air quality [3]. Hygroscopic materials can uptake moisture from the air when its relative humidity increases and release moisture to the air when its relative humidity falls [4]. The moisture buffering effect can moderate the indoor humidity fluctuations and significantly reduce the peak relative humidity. Therefore, energy conservation could be achieved.

A series of moisture properties were proposed to represent the moisture buffering capacity of hygroscopic materials, including the MBV [5]. According to the test protocol, the MBV is a direct measurement of the amount of water vapor absorbed or desorbed by a hygroscopic material when it is exposed to a square wave in daily cycles (for example, 8 hours of high relative humidity at 75% followed by 16 hours of low relative humidity at 33%). The definition and test method of MBV are clear and easy to understand. However, the humidity cycle of square wave signal used in test method merely shows up in real conditions. The results of moisture uptake or release of materials exposed to real climatic conditions calculated by directly using the MBV would be larger than the real value.

In addition to the theoretical research, numerical models which contain the coupled heat and moisture transfer (HAMT) model [6] were developed for dynamical calculations. The HAMT model is now available in several building simulation tools, which could be used to assess the impact of moisture buffering on building energy consumption in different cli-mates. Many researches discussed the moisture effect on building energy performance [7], but few of them particularly focused on the moisture buffering effect and the operation of HVAC system to maximize the benefit of moisture buffering in different cli-mates.

Firstly, a new mathematical expression of MBV is introduced to calculate moisture uptake and release by materials which exposed to different humidity conditions. Secondly, the impact of moisture buffering on building energy consumption in different climates is studied by numerical simulations. Finally, the relationship between the MBV and potential energy saving rate of different hygroscopic materials is also discussed.

2. Theory deduction of moisture uptake/release

2.1. Basic MBV

In a time period t_p, as described in the standard protocol, the time variation of the surface conditions is that: the high humidity (H) is maintained for αt_p hours, and the low humidity (L) maintained for $(1-\alpha)t_p$ hours. The theoretical or basic Moisture Buffer Value can be defined as the value that obtained from dividing the moisture uptake/release by the relative humidity change [8]:

$$MBV_{basic} = \frac{G}{\Delta\varphi} = 1.27\left[\alpha\left(1-\alpha\right)\right]^{0.535}\sqrt{\delta\rho\xi}\sqrt{t_p} \tag{1}$$

Where, G is moisture uptake/release accumulated (kg·m-2), φ is the relative humidity (% or -), δ is vapor transfer coefficient (kg·m-1·s-1), ρ is the density of dry material (kg·m-3), ξ is the moisture capacity (kg·kg-1).

There are three assumptions for the governing equation. (1) The material is considered homogenous; (2) The moisture properties are assumed constant; (3) the initial humidity conditions are uniform throughout the material. These assumptions are reasonable for the moisture buffering in normal domestic buildings, and have been adopted by many studies [9].

2.2. Improved MBV

Considering a real situation, the humidity variations in buildings may not appear to be a square wave function. As a consequence, using the basic moisture buffer value directly to calculate the moisture uptake/release in real climate condition isn't proper. Exploration of the difference of moisture uptake/release when the humidity cycle differs is essential.

In order to facilitate the discussion, it is supposed that the humidity variation in real climate could be considered as a quasi-harmonic function, which can be written as:

$$f(t)=\begin{cases}\phi+(H-\phi)sin\left(\dfrac{\pi}{\alpha t_p}t\right) & when(n-1)t_p<t<(n-1+\alpha)t_p\\ \phi+(\phi-L)sin\left(\dfrac{\pi}{(1-\alpha)t_p}t\right) & when(\mathrm{n}-1+\alpha)t_p<t<nt_p\end{cases} \tag{2}$$

Where, ϕ is the equilibrium relative humidity of material (%). The high humidity range (RH>ϕ) lasts for αt_p hours with the maximum RH at H, and the low humidity range (RH<ϕ) lasts for $(1-\alpha)t_p$ hours with the minimum RH at L.

Considering the moisture uptake process, the absorbed moisture can be expressed as:

$$G_{in}=2(H-\phi)\sqrt{\frac{\delta\rho\xi\alpha t_p}{\pi}} \tag{3}$$

And the released moisture can be expressed as:

$$G_{out}=2(\phi-L)\sqrt{\frac{\delta\rho\xi(1-\alpha)t_p}{\pi}} \tag{4}$$

In a long period, the moisture uptake G_{in} equals to the moisture release G_{out} , so that the moisture uptake/release becomes:

$$G_{in}=G_{out}=2(H-L)\frac{\sqrt{\alpha(1-\alpha)}}{\sqrt{\alpha}+\sqrt{1-\alpha}}\sqrt{\frac{\delta\rho\xi t_p}{\pi}} \tag{5}$$

According to equation (1):

$$G_{in}=G_{out}=0.888\frac{\left[\alpha(1-\alpha)\right]^{-0.035}}{\left(\sqrt{\alpha}+\sqrt{1-\alpha}\right)}MBV_{basic}(H-L) \tag{6}$$

If define a factor β to replace the complicate term in equation (6):

$$\beta=0.888\frac{\left[\alpha(1-\alpha)\right]^{-0.035}}{\sqrt{\alpha}+\sqrt{1-\alpha}} \tag{7}$$

The moisture uptake/release can be rewritten as:

$$G_{in}=G_{out}=\beta MBV_{basic}(H-L) \tag{8}$$

In equation (8), β is a theoretical correction factor for the case of quasi-harmonic humidity variation. When α=1/3, which means the high humidity condition lasts for 8 hours in a daily cycle, β=0.6715.

Equation (8) could be used to represent the moisture transfer into/out the hygroscopic material under real daily weather condition that is similar to the quasi-harmonic function in most cases. In addition, the moisture uptake and release during a longer period of humidity cycles, such as weekly, monthly or even annually variations, could be easily calculated by using the present method.

2.3. Validation of Correction Factor β

A comparison between the present method (calculation based on MBVbasic&β) and advanced simulation (HAMT model) was carried out. Since the HAMT model has been widely tested and validated, the results from the HAMT model is considered to be correct for the comparison and analysis in this research[10]. Four typical building materials were selected. They are concrete, gypsum board, aerated concrete and wood-fiber board. Their MBVs were measured by standard test method. The daily moisture uptake/release can be quickly obtained by Equation (8) and is presented in Table 1. Results from the simulation by HAMT model and the error analysis were also presented in the same table.

Table 1. Moisture uptake/release by different methods.

	Gypsum Board	Concrete	Aerated Concrete	Wood-fiber Board
MBV [$g\cdot m^{-2}\cdot \%RH^{-1}$]	0.60	0.40	0.99	1.17
G-simulation [$g\cdot m^{-2}$]	17.21	11.36	27.52	32.69
G-MBV& β [$g\cdot m^{-2}$]	16.92	11.28	28.20	32.99
Absolute error [$g\cdot m^{-2}$]	-0.29	-0.08	0.68	0.31
Relative error [%]	1.70	0.69	-2.47	-0.94

As seen from the table, a good agreement is found between the results from the MBV method and from the HAMT Model. Relative errors are all less than 3% in each group. More analysis and comparisons were made by using a boarder range of materials in different environmental conditions. The calculation of moisture uptake/release using the MBV and the factor β is proven to be reliable.

3. Simulation and case studies

3.1. Test building and boundary conditions

The BESTEST base case building from the IEA ECBCS Annex 21 was selected as the test building [11]. For simplicity, the windows in south façade were ignored. Materials of all surfaces were set as described in the BESTEST lightweight construction. While the internal surface layers were replaceable. For the cases without moisture buffer materials, the internal surfaces were all supposed to be water-tight. While for the cases with moisture buffer materials, different hygroscopic materials with MBV ranging from 0.5 to 1.5 g·m-2·%RH-1 were selected, and the area of the hygroscopic surfaces changed from 32.4m2 (two internal walls), 75.6m2 (all internal walls), to 171.6m2 (all internal walls + ceiling and floor). The moisture transport through the walls was ignored.

The test building was supposed to be an office. From 09:00 to17:00, it was occupied. The internal heat gain was 15W·m-2; and the moisture gain rate was 6g·m-3h-1. The HVAC system was available to maintain the internal temperature between 20°C and 26°C and control the relative humidity under 65%. During the unoccupied period, the internal heat and moisture gains were zero and the HVAC system was off. The building has an infiltration rate of 0.5ACH throughout the day. Four different cities/climates were chosen in this research, including Shanghai (humid subtropical climate), Beijing (humid continental climate), Paris (temperate climate) and Madrid (Cold semi-arid climate).

3.2. Results and discussion

Indoor hygrothermal conditions of each group were simulated by using the HAMT model. Through comparison of humidity results, it’s clear that the hygroscopic material could decrease the fluctuation of indoor relative humidity.

For the Paris/Beijing cases, the humidity variations (August 01-07) when using 171.6 m2 concrete, gypsum board, aerated concrete or wood-fiber board as the internal surface material were shown in Fig. 1/2.

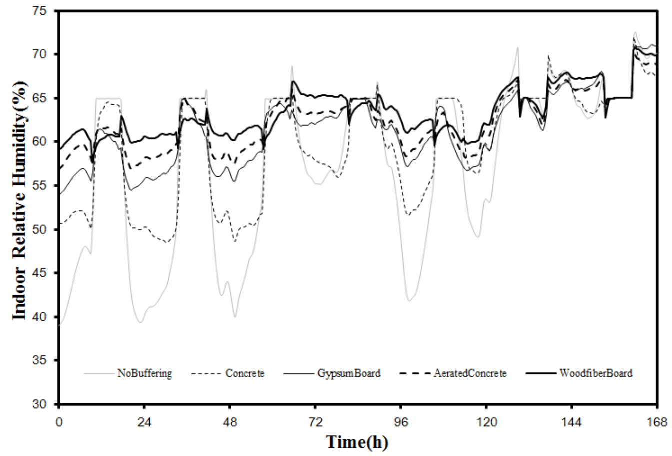

Fig. 1. Relative humidity variations in Paris case.

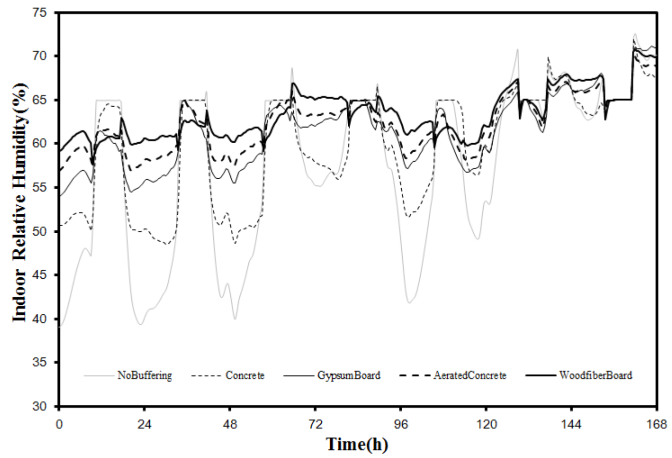

Fig. 2. Relative humidity variations in Beijing case.

The variations of relative humidity in cases with moisture buffering were smaller than that in control case. The trend presents obviously when using aerated concrete or wood-fiber board. The results show that the wood-fiber board and aerated concrete have higher moisture buffering capacities than concrete and gypsum board. For Paris cases, the number of days when there was need for dehumidification was also reduced. While for Beijing cases, lower peak values of indoor relative humidity were realized by using hygroscopic materials.

Energy consumptions (both sensible load and latent load) and energy saving potential of different cases under four climates were got as well. It is noticed that the moisture absorption/desorption during the buffering process may have an impact on the total sensible load. But since the impact is very small, it could be ignored in most cases. Fig. 4 shows part of the results for concrete, gypsum board, aerated concrete and wood-fiber board as the internal surface materials in Paris case. Energy saving rate increases with MBV values.

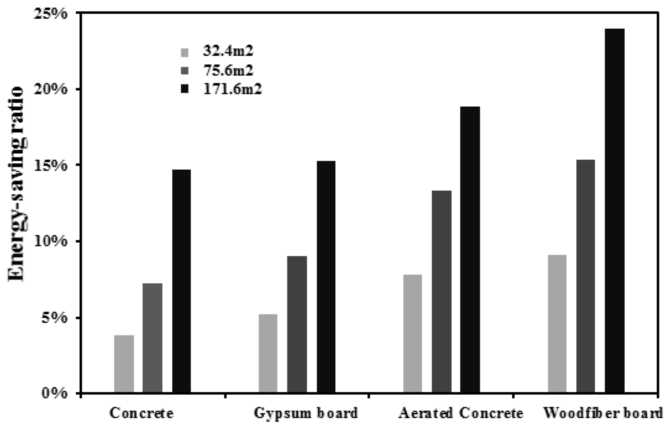

Fig. 3. Energy-saving rates in Paris case.

For the Paris cases (shown in Fig. 3), the energy saving rate could be over 22% when using 171.6m2 aerated concrete or wood-fiber board on the internal surfaces. If using 171.6m2 concrete or gypsum board, or 75.6m2 aerated concrete or wood-fiber board, the energy saving rate could still be around 15%.

A large amount of simulations were carried out to study the energy impact of different hygroscopic materials under different climates. It was assumed that all internal surfaces of the room were covered by hygroscopic materials in the simulation. Table 2 shows the general relationship between MBV values and potential energy saving rates.

Table 2. Relationship between MBV values and potential energy saving rates.

		MBV [g·m-2·%RH-1]		
		0-0.5	0.5-1.0	1.0-1.5
Potential energy-saving rate	Madrid	0-20%	20-25%	25-35%
	Paris	0-15%	15-20%	20-30%
	Beijing	0-5%	5-8%	8-15%
	Shanghai	0-4%	4-7%	7-15%
	Madrid	0-20%	20-25%	25-35%

Although the MBV was developed primarily for characterizing the moisture buffering ability of materials, the present research shows it could also be used as a good indicator for materials' energy saving potential. Architects and engineers could use MBV to choose proper internal surface materials for their green building design. Normally, the higher MBV, the higher energy saving potential. It is important to note that the values presented in Table 2 are estimated. Those values which based on numerical simulation under the above described conditions should be used with caution. More researches of MBV at product level are ongoing, and will be presented in future publications.

4. Conclusion

A new mathematical expression of the moisture buffer value (MBV) and the correction factor β is developed in this paper. It shows high precision to use the present method to calculate moisture uptake/release by hygroscopic materials that exposed to different conditions. The impact of moisture buffering on indoor humidity condition and building energy consumption in different climates is studied by numerical simulations. The results show that the fluctuation of relative humidity could be decreased obviously when applying hygroscopic materials and it is possible to reduce the total energy consumption by up to 25% in the temperate (e.g. Paris case) and semi-arid (e.g. Madrid case) climate zones. The moisture buffer materials have a high performance in the climates that have a distinct humidity difference between day and night. The relationship between the MBV and potential energy saving rate of different hygroscopic materials in different climates is also discussed. Architects and engineers could use MBV as an indicator to choose proper internal surface materials for their energy efficient building design according to the site location (climates), function (residential or commercial etc.) and the goal for energy saving.

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